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Using Automated Scheduling for Analysis of the EMIT Mission

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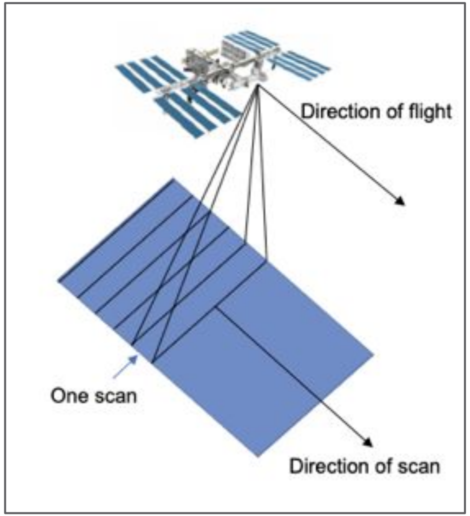
Mission Background

- **E**arth Surface **M**ineral Dust Source **I**nves**T**igation[1]
- Scheduled for launch to the International Space Station in 2022
- Spectrometer in the visible and shortwave-infrared (VSWIR)
- Goal is to map the surface mineralogy of dust source regions to improve atmospheric models

1. https://science.jpl.nasa.gov/projects/EMIT/

CLASP Background

- **C**ompressed **L**arge-scale **A**ctivity **S**cheduling and **P**lanning System[2]
- Chooses orientation and on/off times of space-based instruments that can be modeled as pushbrooms
- Uses the NAIF SPICE[3] toolkit for geometric reasoning
- Squeaky wheel optimization[4] built in but custom schedulers can be plugged in

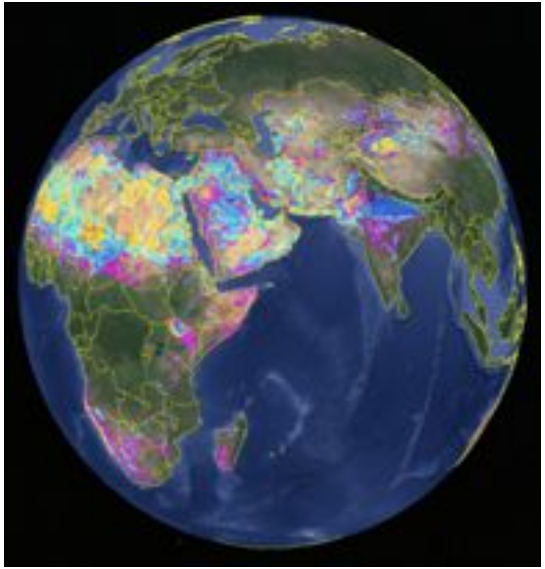


Pushbroom Imager

2. Knight, R., and Chien, S. 2006. Producing large observation campaigns using compressed problem representations. In International Workshop on Planning and Scheduling for Space (IWPSS-2006).
3. Acton, C. 1996. Ancillary data services of nasa's navigation and ancillary information facility. In Planetary and Space Science, volume 44, 65–70.
4. Joslin, D., and Clements, D., "Squeaky wheel optimization," In Journal of Artificial Intelligence Research 10:353-373, 1999.

CLASP Inputs

- Spacecraft ephemeris in the form of spice kernels
- Instrument field of view/pointing capability
- Campaigns
  - Point or polygon on surface of planet
  - Geometric/illumination Constraints



Part of EMIT target region[5]

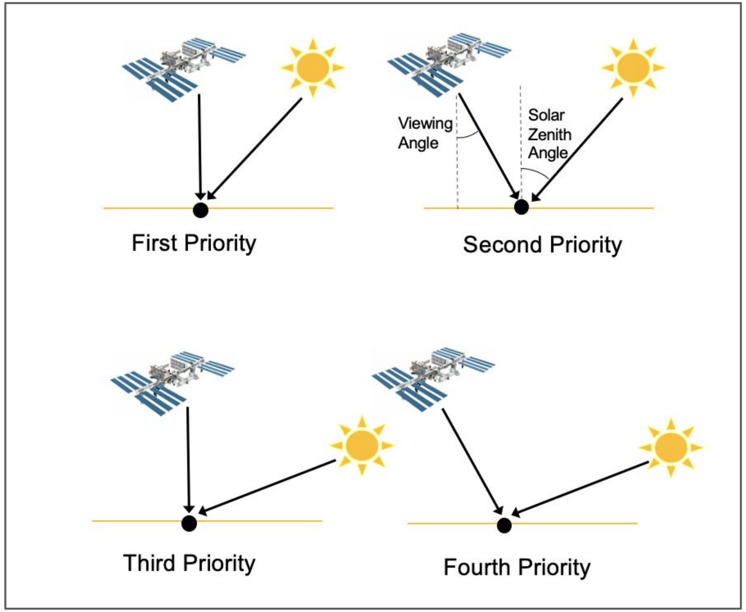
5. Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., and Zhao, M. (2012), Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products, Rev. Geophys., 50

CLASP for Mission Analysis

- Automated Scheduling by CLASP has been used to analyze the effects of variety of factors on EMIT mission success:
    - Observation policy design
    - Hardware configurations
    - Effect of clouds on coverage

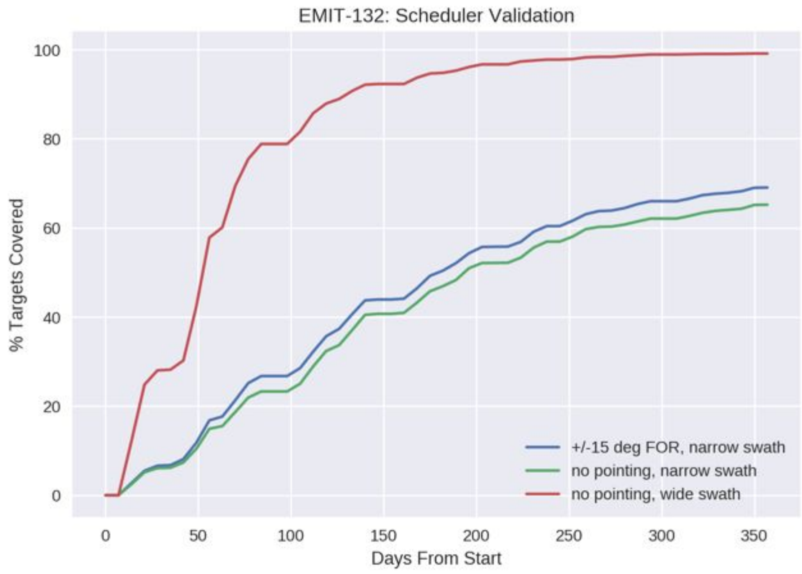
Observation Policy

- In earlier mission planning phase, EMIT instrument had pointing capability
- How to prioritize observations according to pointing and sun angle?
- Highest quality data taken sun is closer to zenith, and instrument is pointed closer to nadir



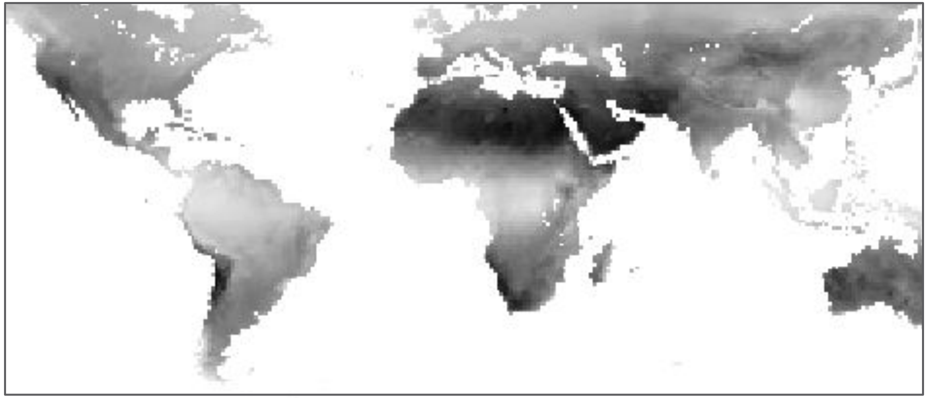
Hardware Configuration: Pointing Mirror

- Examined impact of removing pointing capability on coverage
- Found coverage with:
  - theoretical upperbound with wide swath
  - pointing capability with narrow swath
  - no pointing capability with narrow swath
- Found that with impact of clouds and ISS orbit, pointing capability does not achieve much higher coverage



Effects of Clouds

- Onboard cloud screening software will excise cloudy observations
- Analysed effects on coverage achievable and onboard data volume using mask of cloud probabilities

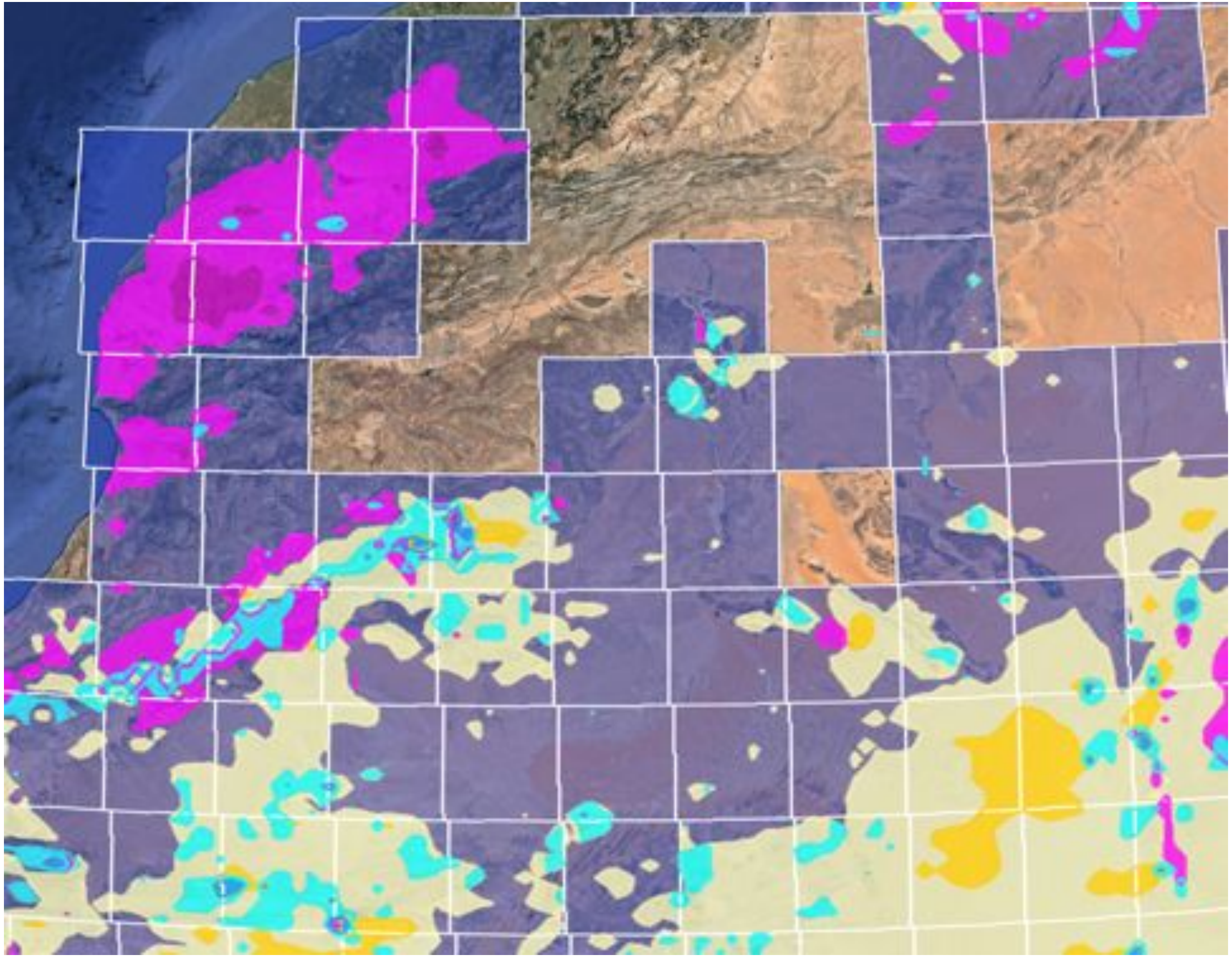


MODIS Cloud Probability Mask[6]
Darker regions have lower probability of clouds

6. Ackerman S. A., and R. Frey, 2015: MODIS Atmosphere L2 Cloud Mask Product (35_L2). NASA MODIS Adaptive Processing System, Goddard Space Flight Center

Coverage Success Criteria

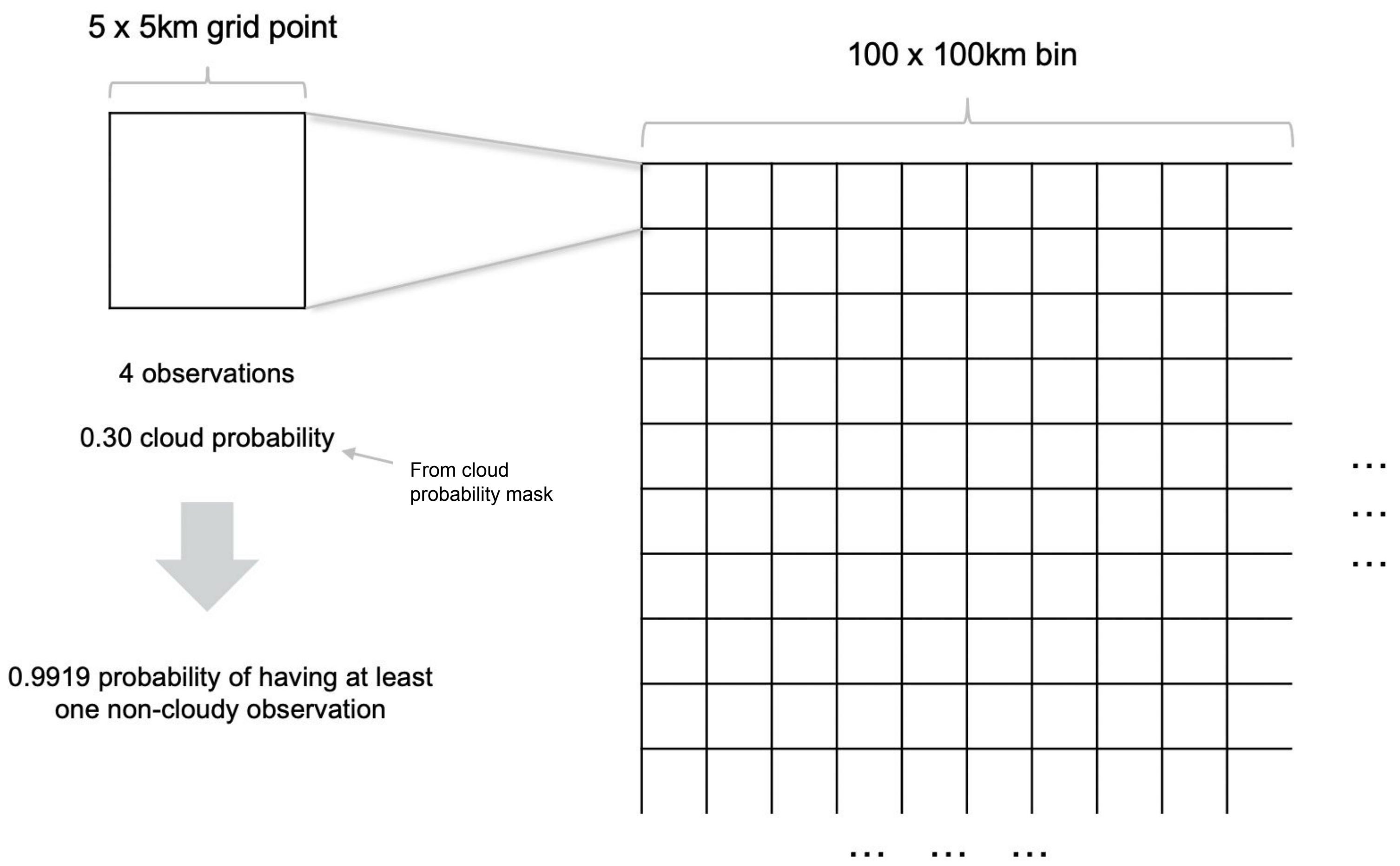
- Given a base target mask, abstract the mask into 100 km x 100 km “bins” with a resolution of 5 km target points within each region
- Analysis regarding two criteria was done:
  - How much of each bin should be covered with cloud free acquisitions to be considered successful
  - Which bins contained enough of the target mask to be of value in the coverage success metric



100 km regions overlaid on initial target mask

Probability of Covering a single 5 km gridpoint

- CLASP produced a schedule over a year, observing each target point whenever illumination conditions met
- Given some 5 km grid point
  - with *N* observations
  - with a cloud probability of *C* obtained from the MODIS cloud mask
  - the probability *P* that the grid point will have at least one non-cloudy observation is
    - $P = 1.0 – C^N$
    - i.e. for grid point with 0.30 cloud probability and 4 observations, P = 1.0 – 0.304 = 0.9919 = 99.19%


5 x 5km grid point
100 x 100km bin
4 observations
0.30 cloud probability
From cloud probability mask
0.9919 probability of having at least one non-cloudy observation
...

Probability of covering a given percentage of a 100 km region

- Given a 100 x 100km bin
  - with 400 contained 5 x 5km grid points
  - with each grid point *g* having some probability P_g of having at least one non-cloudy observation
- Given some threshold *T* of percentage of covered grid points in a bin needed to satisfy the bin
  - The bin has some probability *Q* that *T* or more of its contained grid points have at least one non-cloudy observation
    - $Q = \sum_{i=T}^{400} EXACT(i)$
      - Where *EXACT(i)* is the probability that exactly *i* of the grid points in the bin will have at least one non-cloudy observation
        - Calculated as the (*400 – i*) ‘th coefficient of $\prod(Pgx + (1 - Pg))$ for all grid points *g* in the bin

Probabilities for each 5 x 5 grid point

Threshold of 80% bin coverage needed

Probability of the 100 x 100km bin having at least 80% of grid points covered

ex. 0.93

100 x 100km bin

Each 5 x 5km grid point has some probability of having at least one non-cloudy observation

0.99	0.82	0.93	0.74	0.21	…	…	…	…	…
0.59	0.61	0.72	0.61	0.37	…	…	…	…	…
0.71	0.65	0.93	0.91	0.50	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
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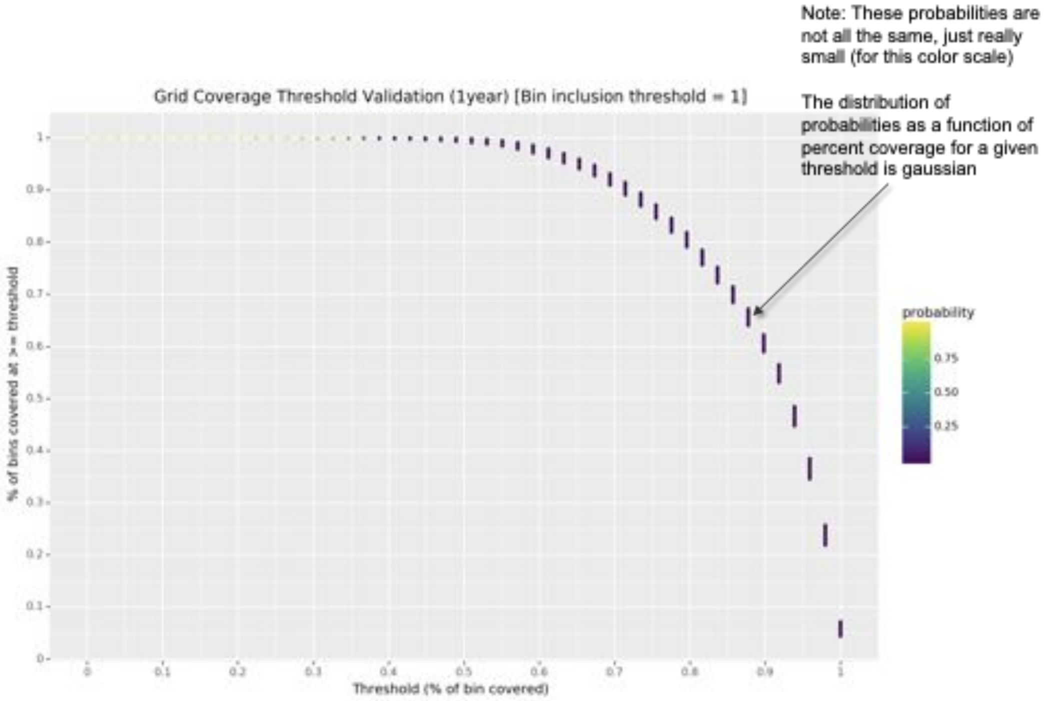
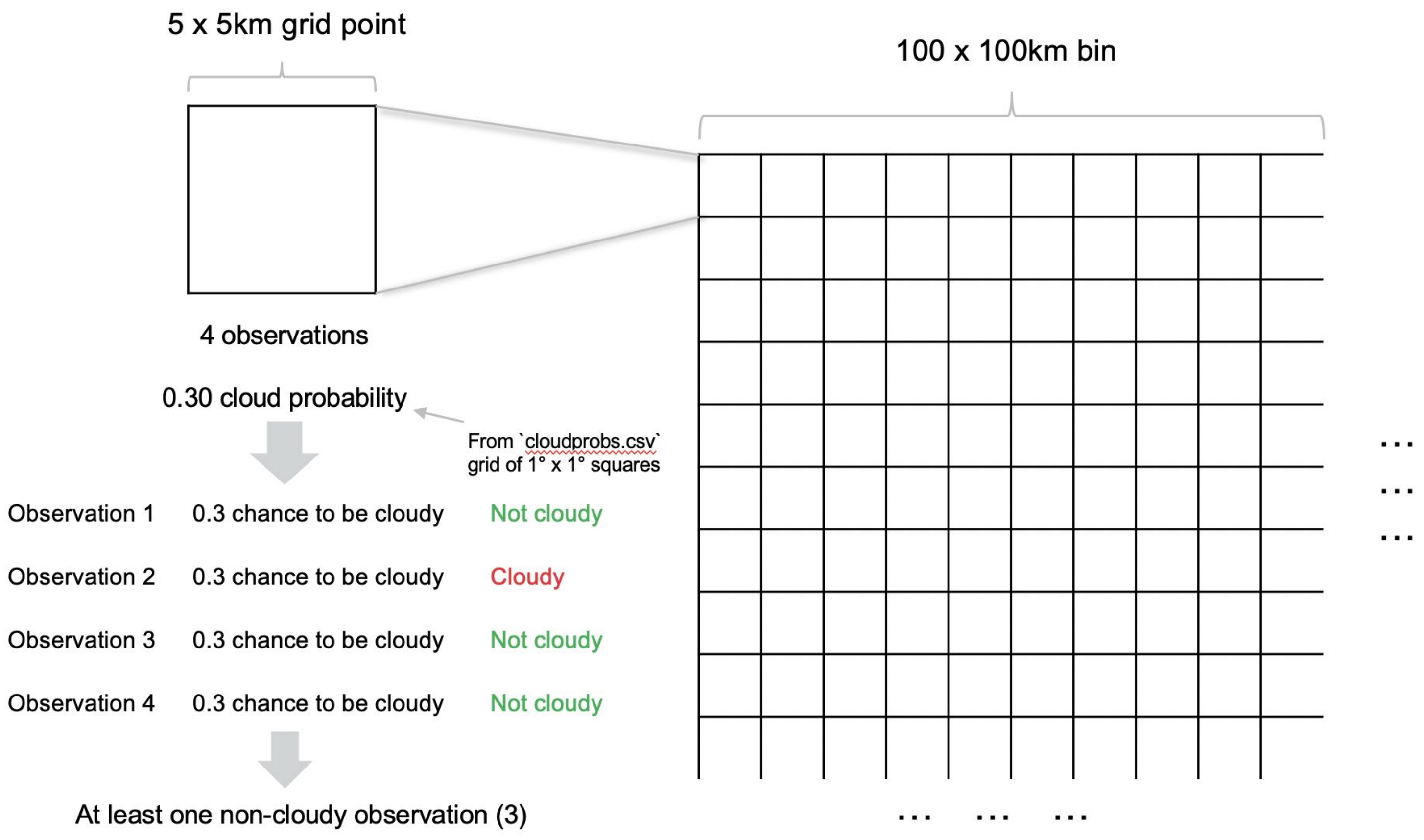
Cloud cover probabilities (overall coverage)

- Given a set *M* of 100 x 100km bins, it has some probability *R* of having exactly *V* percent coverage (given some threshold *T*)
    - Where *V* (percent coverage) can be any portion of the number of bins
    - Ex. For 600 bins V could be 0/600, 1/600, … 599/600, or 600/600



Confirming Probability Propagation

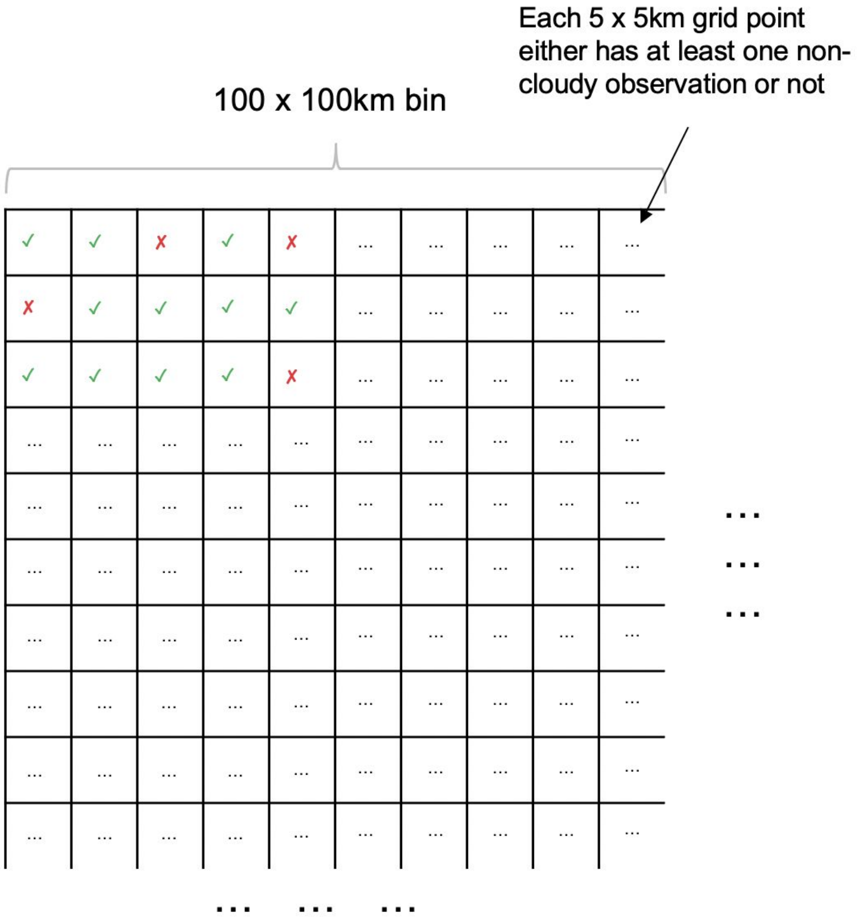
- To confirm that our propagation of the cloud cover probabilities is correct, we compared it to a realization of the schedule
  - For each scheduled observation, lookup its cloud probability and with that chance remove it from the schedule
  - For several different threshold values
    - For each 5 x 5km grid point check if at least one observation is remaining
    - For each 100 x 100km bin check if at least the threshold number of grid points have at least one observation
    - See what percentage of the 100 x 100km bins are satisfied
  - Plot realization results against propagated probabilities


5 x 5km grid point
100 x 100km bin
4 observations
0.30 cloud probability
From `cloudprobs.csv`
grid of 1° x 1° squares
Observation 1 0.3 chance to be cloudy Not cloudy
Observation 2 0.3 chance to be cloudy Cloudy
Observation 3 0.3 chance to be cloudy Not cloudy
Observation 4 0.3 chance to be cloudy Not cloudy
At least one non-cloudy observation (3)
...
...
...
... ...

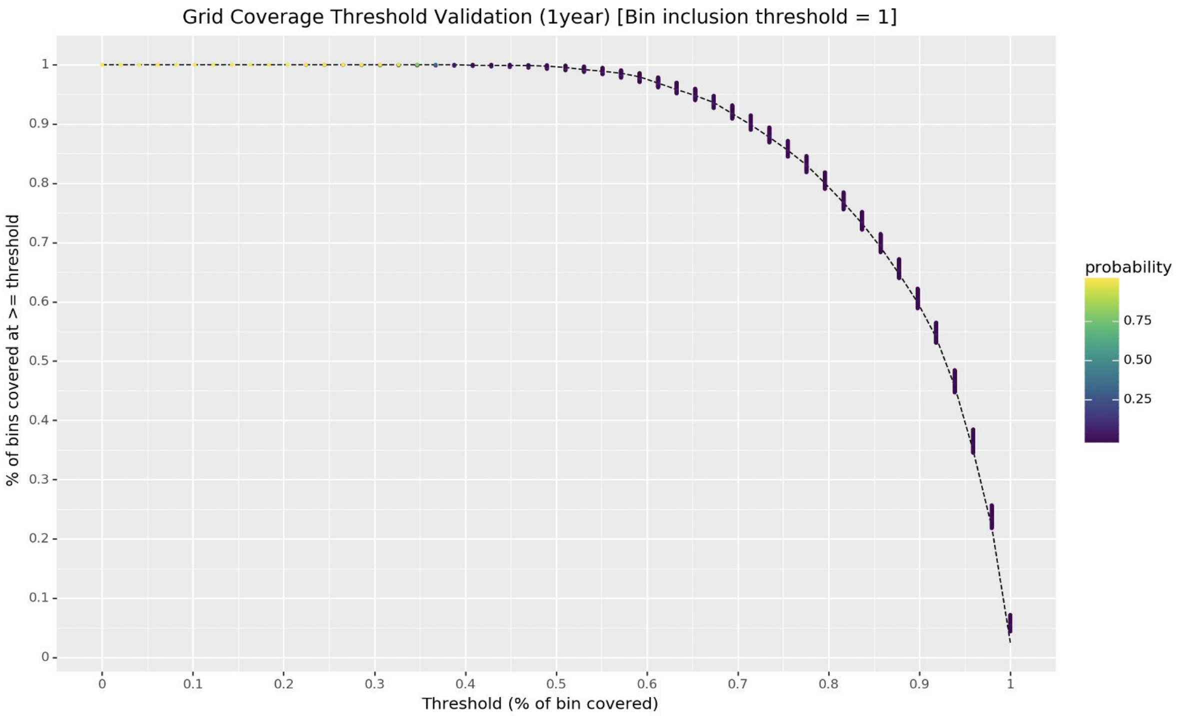
Number of 5 x 5 grid points with at least one non-cloudy observation

Threshold of 80% bin coverage needed

The bin is covered above 80%

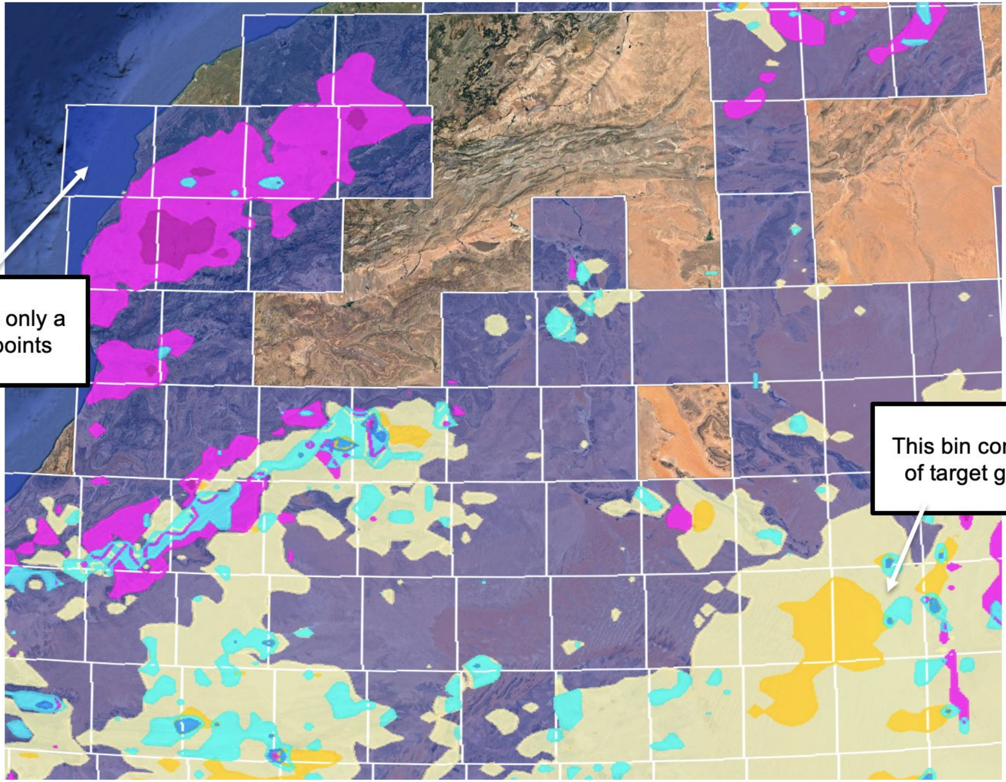


Propagated Probabilities vs Realization Results



Dashed line indicates the coverage percentage achieved in the realization, for the same threshold values as the propagated probabilities

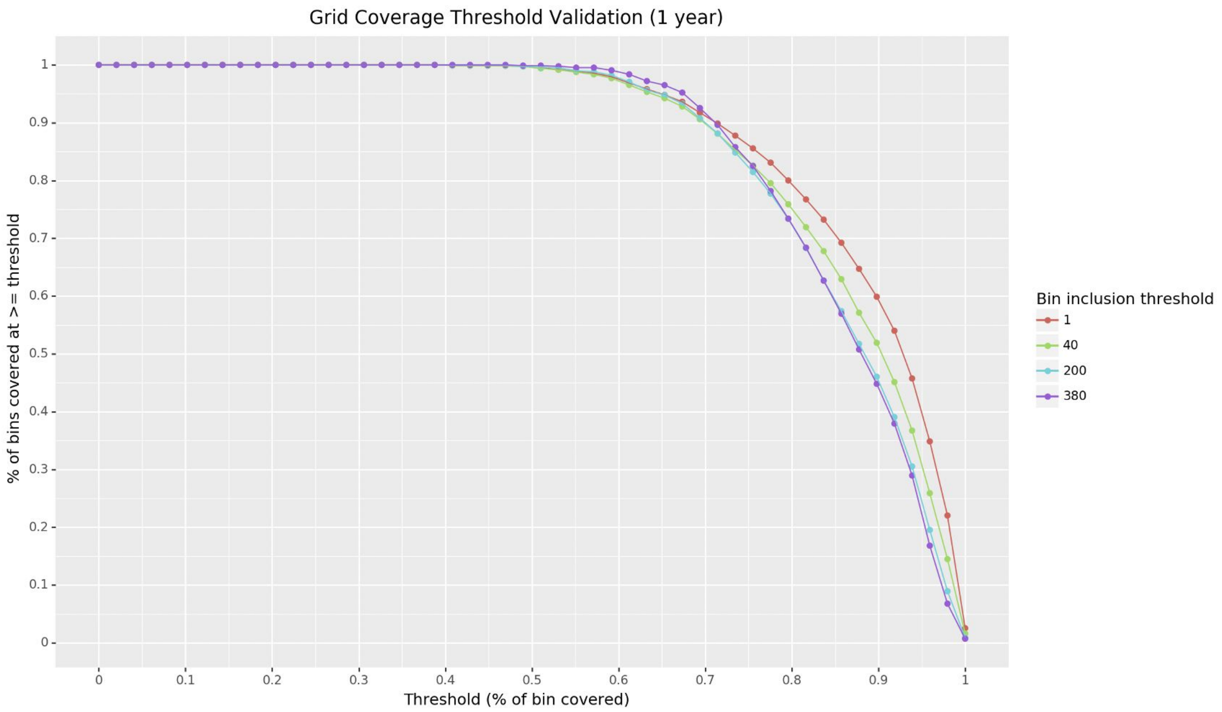
Bin Inclusion Threshold



This bin contains only a few target grid points

This bin contains a lot of target grid points

Comparison of different bin inclusion thresholds



Each line is a realization of a schedule using a different threshold for the number of 5 x 5km grids in the original target map need to be in a 100 x 100km bin to consider the bin

Conclusion

- Automated Scheduling used to aid in many aspects of mission design for EMIT
  - Observation Design
  - Hardware configurations
  - Effect of Clouds on Coverage

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